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DEVELOPMENT AND EVALUATION OF A MODEL FOR POLLUTANT DISPERSION FROM ELEVATED ROADS

James O'Neill[1], Martin Seaton[1], Kate Johnson[1], Jenny Stocker[1] and David Carruthers[1]

[1]Cambridge Environmental Research Consultants, Cambridge, UK

Abstract: This paper presents the development and evaluation of an improved method for modelling elevated road sections in operational (Gaussian-type) dispersion models, which has been implemented in the widely-used ADMS model. While the traditional approach to modelling road elevation allows emissions to disperse freely through the road surface, the new method limits the downward vertical spread of the plume during its traversal over the road carriageway. The new method is evaluated using data from two reference monitors located adjacent to an elevated section of the M4 motorway in London, UK. The first monitor is positioned away from any other heavily-trafficked roads, allowing the new and traditional modelling approaches to be compared with confidence; statistics from one year of hourly output indicate that the new method is better at capturing concentrations measured at this receptor located approximately 7 m from the carriageway edge, though accounting for road elevation - as opposed to modelling the source at ground level - has a much more significant bearing on prediction accuracy. The second monitor is also located next to a busy ground-level road, allowing the relative impact of emissions from the elevated and ground-level road to be assessed. Overall, the evaluation study demonstrates that road elevation leads to significantly reduced ground-level concentrations due to increased source-receptor distances, enhanced dispersion from greater wind speeds at height, and longer dispersion times before ground-level reflections occur. Roads that are elevated above the level of buildings in urban areas also benefit from the reduced impact of pollution build-up resulting from recirculating flow within street canyons.

Key words: *Air pollution, dispersion, modelling, elevated roads, ADMS, flyovers, evaluation, validation*

INTRODUCTION

Urban areas typically suffer from poor air quality, commonly due to road traffic emissions of pollutants such as NO_X, NO_2 and particulates. Urban morphologies often include complex road geometries, such as elevated road sections and street canyons, which can significantly alter how these pollutants disperse away from emissions sources. Whilst good progress has been made in street-scale atmospheric dispersion models in terms of modelling street canyon effects (Vardoulakis *et al.*, 2007, Hood *et al.*, 2021), comparatively little attention has been given to better capturing the effects of road elevation on dispersion. Most Gaussian-type dispersion models neglect to capture the shielding effect of the elevated road surface to downward spread that occurs as the plume passes over the road structure, instead only accounting for reflections once the plume has reached the ground. This omission has prompted a study concerned with developing improved modelling approaches for elevated roads which can be used to better quantify the influence of road elevation on ground-level pollutant concentrations.

This paper presents recent work undertaken by Cambridge Environmental Research Consultants (CERC) to develop an improved approach to modelling elevated flyover-type road sources, where the wind can flow largely unimpeded both over and under the elevated road surface. The new approach limits the downward vertical spread of the plume over the elevated road surface and has been implemented in the widely-used urban dispersion model, ADMS. An evaluation of the updated model is presented using data from reference monitors located next to an elevated section of motorway in London, UK.

NEW METHODOLOGY

The traditional approach to modelling elevated roads in Gaussian-type models allows vehicular emissions to disperse freely through the road surface. With this approach, the vertical concentration profile at a given downstream distance is described by (in stable/neutral conditions) a single Gaussian distribution, with reflections off the ground and boundary layer top (**Figure 1(a)**).

The new approach in ADMS limits the downward spread of the plume to be h_0, the initial road mixing height (taken as 1 m), during its traversal over the road carriageway, while the upward spread increases freely from the point of release. Downwind of the road carriageway, the downward spread increases freely as it would have done from the point of release with the traditional ADMS road source modelling approach (CERC, 2021). With this new approach, the vertical concentration profile at a given downstream distance is described by two adjoining half-Gaussians with the same amplitude (to ensure continuity in the concentrations) but differing standard deviations (**Figure 1(b)**).

Recalling that the downwind concentration in Gaussian-type models can be expressed as $C = \frac{Q}{U}g(y)f(z)$, where Q is the source strength, U is the wind speed (at the mean plume height) and $g(y)$ and $f(z)$ are the transverse and vertical concentration distribution functions whose full integrals are both unity, the vertical concentration distribution function with the new approach is given by:

$$f(z) = \frac{2}{\sqrt{2\pi}(\sigma_{z_-} + \sigma_{z_+})}\left[\exp\left(\frac{-(z-z_p)^2}{2\sigma_{z_-}^2}\right)\left(1 - \mathrm{H}(z-z_p)\right) + \exp\left(\frac{-(z-z_p)^2}{2\sigma_{z_+}^2}\right)\mathrm{H}(z-z_p) + \text{reflection terms}\right] \quad (1)$$

where σ_{z_-} and σ_{z_+} are the standard deviations of the lower and upper half-Gaussians respectively, z_p is the plume centreline height, H denotes the Heaviside function and 'reflection terms' represent extra terms accounting for reflections off the ground and (in the presence of a temperature inversion) the boundary layer.

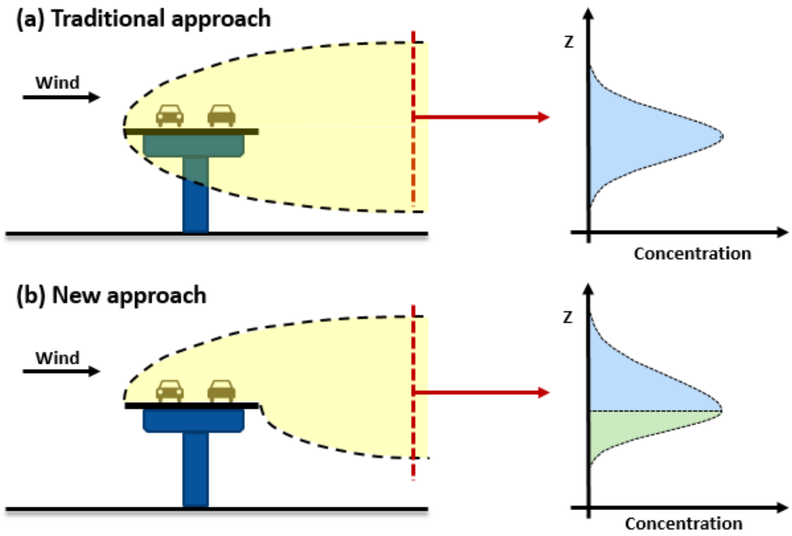

Figure 1. Schematic of the traditional (a) and new (b) approach to modelling an elevated road source in ADMS.

EVALUATION APPROACH

Multiple sites where concentration measurements have been recorded close to elevated road sections were identified for the evaluation of the new modelling approach. For brevity, only the evaluation using data from two nearby UK Automatic Urban and Rural Network (AURN) monitoring stations in London is presented here; the reader is referred to Stocker *et al.* (2020) for full evaluation results at all selected sites.

Both AURN monitors are located next to the M4 flyover in Brentford, London (**Figure 2**). Monitor HS010 is located in a park away from any other heavily trafficked roads, making it an ideal site for model evaluation purposes. This monitor is approximately 7 m from the edge of the M4 with an inlet height of 1.7 m. Monitor HS5 is located alongside the (busy) A4, which runs underneath the M4, making it an ideal site for comparing the relative impact of elevated versus ground-level roads. This monitor is approximately 9 m from the edge of the M4 (4.5 m from the edge of the A4) with an inlet height of 2.5 m.

Details about the setup of the ADMS model are now given. The M4 and A4 were represented as explicit road sources. The elevation of the M4 was taken as 6 m. Hourly traffic data from Highways England's WebTRIS was used for the M4 sections, Department for Transport (DfT) traffic data was used for the A4 (vehicle count data for a single 12-hour period) and the Emission Factors Toolkit (EFT) v9.0 dataset with real-world NO_X adjustments (Hood *et al*., 2018) was used to calculate the resulting emissions. Emissions from all other local sources were represented using (10 m depth) volume sources, with emission rates taken from the London Atmospheric Emissions Inventory (LAEI). Background concentrations at the study site were taken from a wind-direction-dependent combination of four AURN monitors: Lullington Heath, Chilbolton, Rochester Stoke and Wicken Fen. The model's Chemical Reaction Scheme was used to account for photochemical reactions between NO, NO_2, O_3 and VOC. The hourly meteorological data used to drive the model was taken from the Met Office's weather station at Heathrow airport. One year (2019) of meteorological data was used as input to the dispersion model, with the resulting model output compared against contiguous concentration measurements from the two AURN monitors. The A4 section next to the HS5 monitor was modelled as an asymmetric canyon using the ADMS advanced street canyon module to account for the row of tall buildings on the monitor side of the road (**Figure 2**).

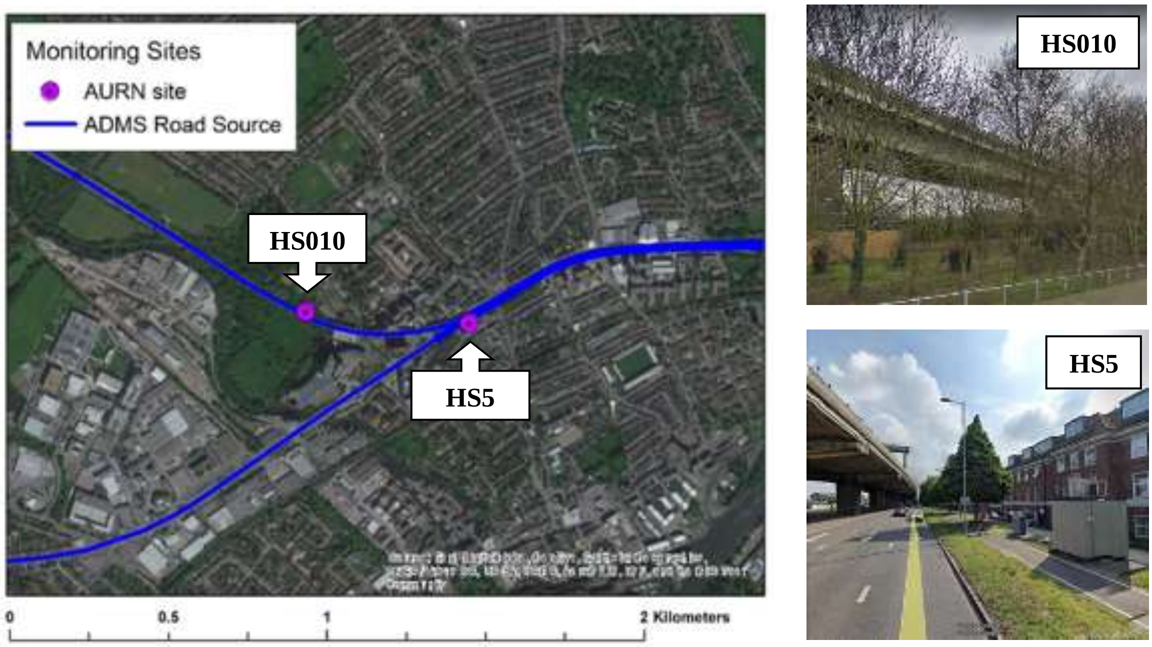

Figure 2. Location of modelled roads and reference monitors at the Brentford site (left) and Google Street View images near each monitor (right) (note the HS010 monitor cannot be seen directly using Google Street View but is just to the right of the photo). Source: ESRI *et al.* (left), Google Maps (right).

RESULTS AND DISCUSSION

We first compare monitored against modelled concentration data from the HS010 site, where the elevated M4 constitutes the only nearby major source of traffic emissions. Three separate approaches to modelling the M4 are considered: modelling it at ground-level ('Flat'), modelling it at elevation using the traditional approach ('Old') and modelling it at elevation using the new approach ('New').

Table 1 presents statistics relating to each modelling approach for pollutants NO_X and NO_2. Shown are the annual average monitored and modelled concentrations, normalised mean square error (NMSE), correlation coefficient, fraction of points within a factor of two of the monitored values (Fac2) and the fractional bias (fb). NMSE and fb have an ideal value of zero, while correlation and Fac2 have an ideal value of unity. The modelled vs monitored annual average data are also presented as a scatter plot (**Figure 3**). The new approach gives the best statistics for all but the NMSE for NO_X, where the 'Old' statistic is slightly better. As expected, the annual average concentrations are significantly over-predicted when the road is modelled at ground-level (+116% for NO_X, +67% for NO_2), primarily due to the decreased vertical distance between source and receptor. The traditional approach leads to a slight over-prediction (+14% for NO_X and NO_2)

due to the unimpeded spread of the plume through the elevated road surface. The percentage difference between monitored and modelled annual mean concentrations is further reduced (-7% for NO_X, +3% for NO_2) using the new approach as a result of better accounting for the shielding effects of the road surface to downward spread during traversal of the plume over the road carriageway.

Table 1. Statistics from modelling at the HS010 site. Best statistics (per pollutant) are shaded grey.

Pollutant	Approach	Monitored mean (μg/m³)	Modelled mean (μg/m³)	NMSE	Correlation	Fac2	fb
NO_X	Flat	46.2	99.8	2.443	0.344	0.362	0.735
NO_X	Old	46.2	52.6	1.211	0.515	0.621	0.131
NO_X	New	46.2	42.8	1.285	0.557	0.708	-0.076
NO_2	Flat	26.0	43.5	0.872	0.496	0.584	0.503
NO_2	Old	26.0	29.6	0.387	0.628	0.785	0.130
NO_2	New	26.0	26.7	0.360	0.646	0.802	0.026

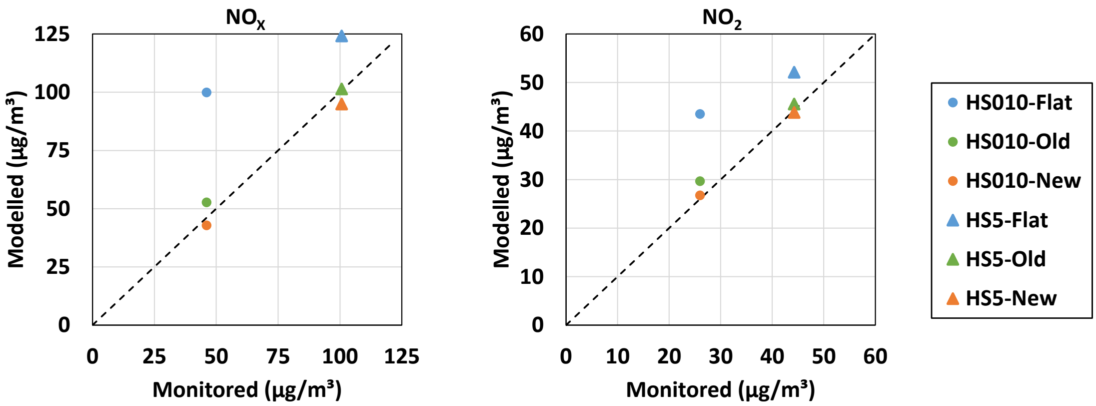

Figure 3. Modelled vs monitored annual average NO_X and NO_2 scatter plots at the HS010 (circles) and HS5 (triangles) sites for the 'Flat' (blue), 'Old' (green) and 'New' (orange) modelling approaches.

Next, we analyse the HS5 site dataset to compare the relative impact of the local elevated road source to the ground-level road source. Despite significantly higher uncertainty in terms of road traffic emissions data for this site, where the traffic data for the A4 is taken from a single, weekday 12-hour count in contrast to the hourly dataset available for the M4, the annual average modelled concentrations (**Figure 3**) again show good overall agreement with the monitored values using the new approach. Looking in more detail, **Figure 4** shows modelled source apportionment results for NO_X concentrations, in which the data have been binned according to wind direction (using 10° sectors). Concentration contributions are shown for the elevated M4 road, the ground-level A4 road, other local (volume) sources and background concentrations. Also shown are the corresponding (total) monitored concentrations. The plot again demonstrates good overall model performance using the new approach, with which the concentration variation with wind direction is generally well-captured. The source apportionment results indicate that the receptor concentrations are significantly more affected by the ground-level A4 (grey) than the elevated M4 (yellow), thus highlighting the benefits that elevated road sections can have on reducing ground-level concentrations. The relatively low impact of the elevated road can be explained by the increased vertical distance between the source and the receptor as well as the increase in wind speed with height, which leads to enhanced dispersion (dilution) of the plume. Ground-level reflections that increase concentrations due to plume 'folding' also occur further from the source. Recalling that the M4 is aligned at an angle of approximately 60°, we see that the highest impact of the elevated M4 on monitored concentrations occurs when the wind is aligned with the road. Between 100° and 220°, the wind blows the elevated emissions away from monitor side, hence why we see almost no M4 contribution in this sector. When the wind advects pollutants the other way, from the M4 towards the monitor, the plume does not have much distance over which to spread vertically downwards by the time it reaches the monitor i.e. the plume remains largely above the monitor. However, for along-road flow, the plume has a longer time to disperse downwards after leaving the road carriageway prior to reaching the monitor.

Conversely, the ground-level A4 contribution remains fairly constant across all wind directions. The green line in **Figure 4** ('Without AC') shows total modelled concentrations per wind sector when the A4 is modelled as an open road source as opposed to an asymmetric street canyon. When the presence of the buildings adjacent to the HS5 monitor are not accounted for in the model configuration, while the model performs well for wind directions between 0° and 100°, and 220° and 360°, for wind directions between 100° and 220°, the model significantly under-predicts concentrations. This corresponds to when the prevailing wind advects from the monitor to the road. The model results using the advanced street canyon module, which compare much better with the measurements, suggest that the presence of these buildings generates a recirculating cell that causes the near-ground traffic emissions to disperse in the opposite direction to the prevailing wind, i.e. from the road towards the monitor. The impact of these street canyon effects are reduced for the elevated road, also helping to keep ground-level concentrations down.

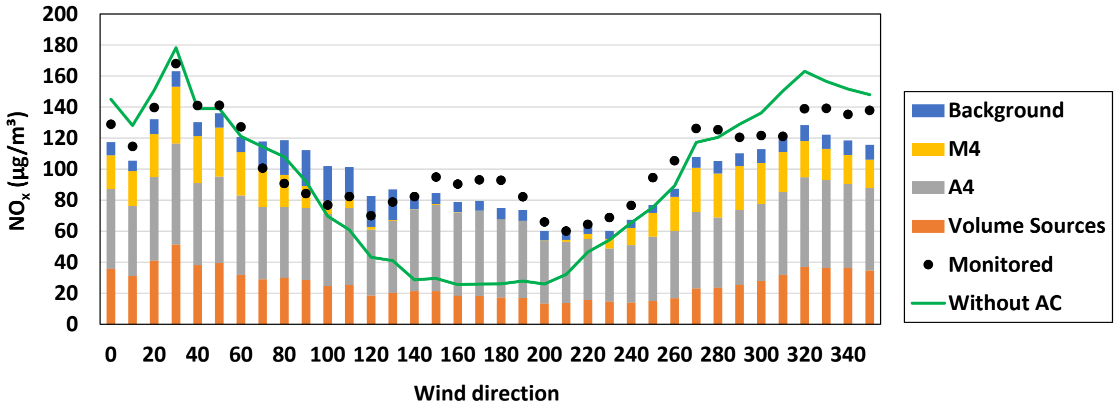

Figure 4. NO_X source apportionment by wind direction using the new approach at the HS5 site.

CONCLUSION

A new approach to modelling flyover-type elevated road sections has been implemented in the widely-used ADMS dispersion model. An evaluation study comparing modelled concentrations against reference monitor data recorded near elevated road sections demonstrates good model performance using this new approach. Elevated roads have relatively low impact on local ground-level concentrations due to: increased source-receptor distances; enhanced dispersion relating to increased wind speed at source height; and plume spread both upwards and downwards once off the road. Additionally, road elevation in urban areas can reduce the impact of street canyon effects, whereas emissions from ground-level roads can become trapped leading to increased concentrations.

ACKNOWLEDGEMENTS

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